Electrical potential techniques for damage detection in carbon fibre composites

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INTRODUCTION

In the electrical potential technique for damage sensing in carbon fibre reinforced polymers (CFRP), fibre fracture and delamination cracks modify the current flow and potential fields in the composite. By monitoring the potential field on the surface of the composite, changes in the field may be related to the location and extent of any damage present.

The technique was first suggested by Schulte [1]. Since then, many workers have examined its application to monitoring fatigue damage [2 - 5] and to location of impact damage. [6-8] Its use has also been suggested for strain sensing [9], and for the measurement of delamination crack growth [10].

The technique is extremely simple in principle, and does not involve the use of any embedded sensors such as fibre optic cables or piezo sensors, these and other artefacts are required for monitoring damage for example via acoustic emission or using embedded emitters and detectors [11,12]. However, the requirement for a network of electrodes for measurement of local potential at locations remote from the damage point will still involve attachment or possibly embedding of electrodes. These must be mechanically robust and maintain good electrical contact with the carbon fibres within the composite. In addition there will be many parameters other than mechanical damage, which will cause changes in the value of potential measured at a point. Examples include mechanical strain [2, 4], changes in temperature [13], changes in the level of moisture within the composite. The extent to which these change the potential, in comparison with the changes, which are produced by impact damage, will set limits to the sensitivity and viability of the technique.

Electrical conduction in carbon fibre reinforced polymers

In a unidirectional carbon fibre – epoxy laminate, if current is introduced into the sample ends and flows parallel with the fibres, the resistance of the composite in this direction is given by

$$Rc = \rho_f L / A_c V_f + 2R_e$$

where,

ρ_f is the fibre resistivity,

A_c is the area and L the length of the composite

V_f is the volume fraction of fibres

R_e is the resistance of the electrodes

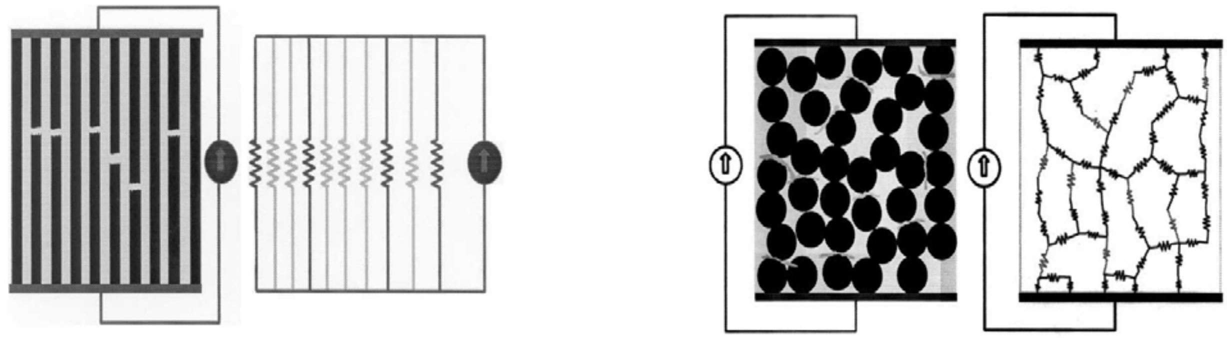
The composite resistivity in this direction is given by

$$\rho_c = \rho_f / V_f$$

As typically ρ_f = 0.018-0.020 mΩ m, typical values of unidirectional composite resistivity for volume fraction of 50-60% found in engineering composites is 0.03-0.04 mΩ m. This is in reasonable agreement with experimentally measured values [2].

Perpendicular to the fibres, electrical conductivity is via fibre to fibre contact in a complex 3D network, and measured values of resistivity are about 10^3–2×10^3 times greater than the longitudinal values [2]. Values of 100-400 mΩ m have been recorded for resistivities in this orientation [2].

When damage in the form of fibre fracture occurs, then this will disturb the potential fields, locally and remotely will change the overall resistivity. Delaminations will locally greatly increase the resistance of the interface between individual fibres and between the laminae in the composite, and will once again locally disturb the potential fields. The processes are illustrated schematically in figure 1.



(a) (b)

Figure 1: Schematic diagram showing the damage mechanisms of (a) fibre fracture (b) matrix fracture between the fibres, and their electrical analogues

For most engineering applications, multidirectional rather than unidirectional laminates are used, and current flow processes will become more complex. These complex flow patterns must be interpreted if damage is to be detected and located using this technique. There will be an interface conductance measured [8] as 0.000125 S/mm^2 for a 0/90 interface. The interface conductance has been shown to vary with mutual misorientation of the laminae, from zero for zero degree misalignment, to 0.000125 for 90° misorientation. This interface conductance will be important in three-dimensional current flow through the laminate.

In the present investigation, external surface potential fields produced by current flow in cross ply [0, 90] and quasi-isotropic [0, 45, 90] laminates has been measured. The influence of holes and impact-induced delaminations on the measured potential distributions has been determined. The results have been compared with theoretical models of current flow calculated using finite element analysis. The results are considered in the light of practical requirements for a damage sensing and locating system.

EXPERIMENTAL

Samples of cross ply and quasi-isotropic CFRP laminate, 240x250x2mm were manufactured from Hexcel HTA/914 continuous fibre prepreg. The lay-up of the two laminates were $[(0/90)_4]_s$ and $[0_2/45_2/90_2/\text{-}45_2]_s$. The samples were laid up and cured in accordance with the manufacturer directions. One surface of each sheet (referred to subsequently as the top) was instrumented with a rectangular grid of 120 electrodes to monitor the local potentials. The grid was on a side of 25 mm. The electrodes were manufactured by abrading each location, where the electrode was to be positioned to expose the carbon fibres. A fine wire was positioned on the electrode site, and the contact between the carbon fibre and the copper wire made with silver dag, a conductive paint. This was then reinforced with an external layer of epoxy to make the electrode mechanically robust.

Additional electrodes were placed at the corners and at the mid points of the of perimeter sides on the bottom surface of the sheet. These were for current introduction. In some experiments, current was introduced at the equivalent sites on the top surface. The effect of current input and output location on the potential distributions was systematically investigated. A 100 mA current was supplied to pairs of current input electrodes from a constant current calibration source. Potentials at the measurement probes were measured with a high impedance digital voltmeter and recorded by a PC. Curve fitting software was used to generate equi-potential contours to define the potential distribution on the top surface of the laminate.

To create damage in the laminate, in a first series of experiments, circular holes were drilled in the samples. These were a worst case damage situation, in which fibres were cut and there was zero current flowing through the thickness of the laminate. Secondly, samples were subjected to impacts of a range of impact energies from 2-8 Joules. The damage produced by the impacts was quantitatively measured using an ultrasonic C scan. This showed that the delaminated areas produced by the impacts were as shown in Table I. Electrical potential distributions were recorded before and after impact and before and after the holes were drilled.

Table I
Damage extent under various impact energies

Impact energy Joules	Delamination size (mm)
2	0
4	18 X 18
6	43 X 26
8	89 X 36

FINITE ELEMENT ANALYSIS

A finite element model for current flow was developed to predict potential distributions in both damaged and undamaged CFRP laminates. The potential distribution was calculated for $[(0/90)_4]_s$ and $[0_2/45_2/90_2/-45_2]_s$ laminates. Each ply was defined by 11303 nodes and 6672 elements. The mesh size was refined through the thickness of each ply and around the delaminated area in order to improves accuracy. The through thickness resistivity of each ply was considered to be homogeneous and equal to the measured transverse unidirectional ply resistivity of 310 mΩ m. Along the fibre direction the resistivity was set at 0.022 mΩm. A current of 100 mA was applied to the node corresponding to the current input probe.

The electrical field in the plate is governed by Maxwell's equation of conservation of charge and the electrical current flowing at the interface between two surfaces is modelled as:

$$\boldsymbol{J=g(V_A-V_B)} \qquad \textbf{(1)}$$

Where J is the current density flowing across the interface from node A on one surface to node B on the other, V_A and V_B are the electrical potential on the opposite sides and g is the electrical conductance at the interface. For $[(0/90)_4]_s$ and $[0_2/45_2/90_2/-45_2]_s$ laminates the contact between two plies of different direction is characterised by the interface conductance. The interface conductance $g_{0/90}$ between a 0° and 90° ply was set as 0.125 S/mm^2 [8]. For $[0_2/45_2/90_2/-45_2]_s$ laminates, this same conductance was assumed for all interfaces.

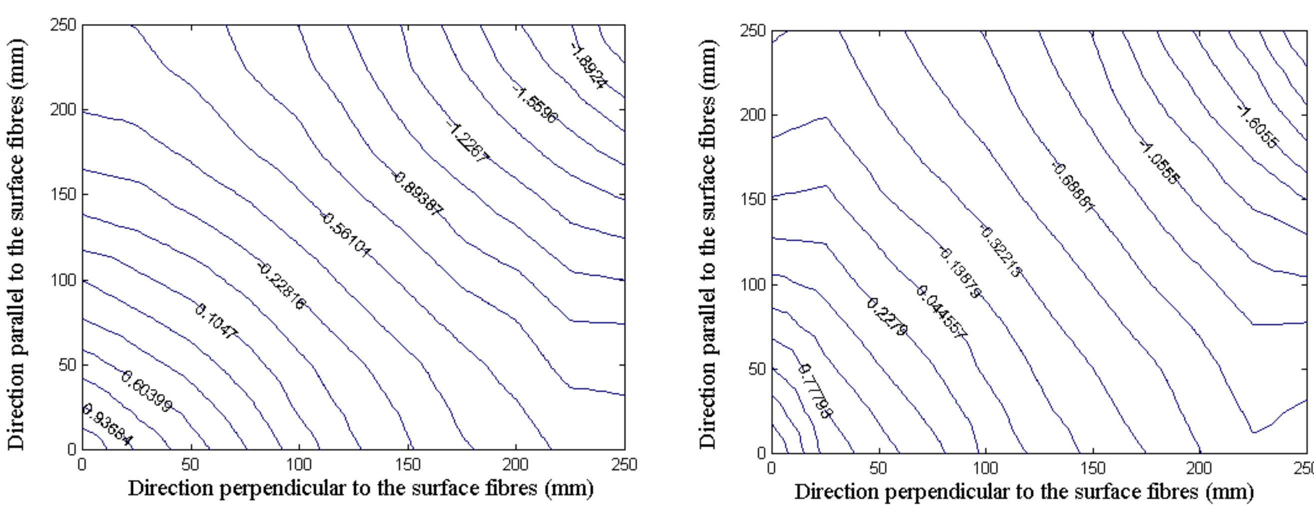
The interface conductance values used in the FE model are respectively 1000 times greater than the experimentally measured values of 0.000125 S/mm^2. It was found that use of experimentally measured values of the interface conductance, resulted in very large discrepancies between the actual potential values and the calculated ones. This discrepancy is believed to be a consequence of differences in the way in which the finite element model simulates the interface, and the discrete microscopic contact points observed in reality [14].
Delaminations were simulated in the finite element model by setting the interface conductance to zero over an area corresponding to the delamination area. The mesh was locally refined at the

edge of the delamination in order to adequately model the rapidly changing potential field in this region. Delaminations were shaped as an ellipse, elongated in the fibre direction, and sizes of 20 X 20 mm, 28 X 40mm, 32 X 50mm 34 X 60mm 36 X 70mm and 38 X 80mm were all modelled. Simulations were of a single layer of delamination between the 90° and 45° laminae.

RESULTS

Potential fields on the surface of undamaged laminates

Figure 2 shows typical potential distributions on the surface of cross ply and quasi-isotropic laminate, for current input on the lower surface at the diagonally opposite corners. The fibre direction in the uppermost layer is from top to bottom of the picture. It will be seen that in both types of lay-up, the equi-potential contours are approximately perpendicular to the line joining the current input electrodes, without a pronounced distortion towards the direction of the fibres. There is a slight rotation in the quasi-isotropic plate towards the underlying 45° lamina. In the cross ply plate the underlying lamina will be 90° to the surface fibres. The overall symmetry of



a

b

Figure 2: Experimentally measured potential distribution on top surface of (a) cross ply and (b) quasi-isotropic laminatee. Current introduction bottom surface, on opposite diagonals

the contours suggests that despite the great electrical anisotropy of individual laminae, the presence of layers of differing orientation with electrical conductivity between them, produces potential fields which in two dimensions are characteristic of an electrically isotropic material.

Whereas the lay-up of the composite appears to have little effect on the potential field distributions. The position of the current introduction electrodes changes the field orientation significantly. This can be seen in figure 3, which is for the same quasi-isotropic distribution as

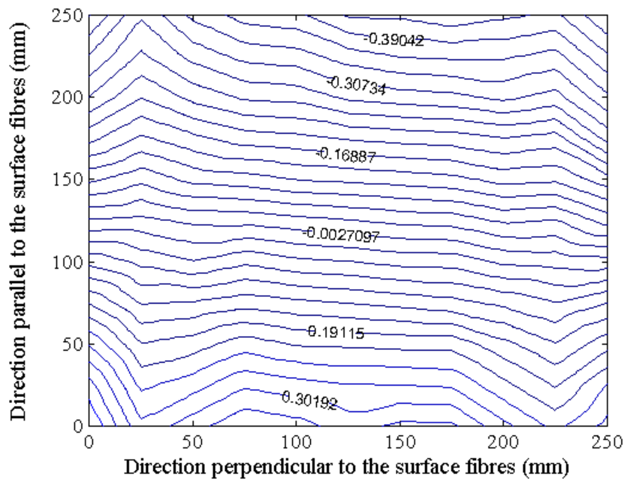


Figure 3: Experimentally measured potential distribution on quasi-isotropic laminate with current introduction on the bottom surface on mid point of horizontal perimeter edges.

in figure 2b, but with the current electrodes located on the bottom surface of the laminate at the mid points of the horizontal sides. Again it can be seen that the equi-potential contours are oriented almost perpendicular to the line joining the current input points, with a small rotation towards the 45° orientation of the ply underneath the surface lamina. There is a slight departure from this picture at the edges of the laminate where distortion from this picture occurs, most probably due to edge effects.

Finite element simulation of surface potential fields in undamaged laminates

Figure 4 shows the simulation of the situation in figure 3, with a quasi- isotropic laminate and current being input on the bottom surface at the mid points of the horizontal edges of the sheet. The similarity between the two distributions can clearly be seen, with the exception of the experimentally measured distributions at the left and right hand edges. The finite element simulation predicts similar potential values to those found experimentally, and the orientation of the equi-potential contours with respect to the line joining the current input and output electrodes, is also almost identical – almost 90° to the line, with a slight rotation towards the orientation of the 45° layer immediately underneath the outermost lamina.

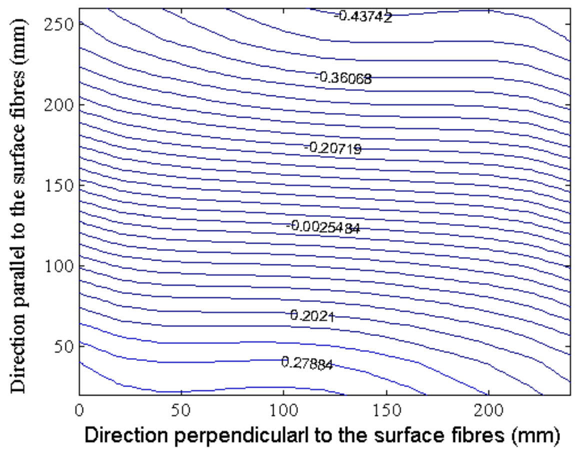


Figure 4 Numerical potential distribution on the top surface of a quasi-isotropic laminate current introduction mid point of horizontal perimeter edges, top surface.

Potential distributions in damaged laminates- holes

Figures 5 and 6 show measured potential distributions around two different sizes of hole 15 mm and 45 mm in diameter in cross ply laminates. The current input positions are half way along the horizontal perimeter edges, with the current flowing parallel to the fibre orientation in the upper surface. The local field distortion around the hole may easily be seen. Of more relevance than equi-potential contours are contours of equi-potential changes and these are shown for the 15 and 45mm diameter holes in figures 7 and 8. In these figures, the contours represent equal values of potential change from before the insertion of the hole compared with after. In both diameters, the greatest change occurs in two bands on each side of the hole, extending in a direction parallel with the fibres and towards the current introduction electrodes. The region of greatest change occurs at a point on the line connecting the current input electrodes, adjacent to the perimeter of each hole. The maximum value of change is greatest adjacent to the 45 mm hole, with a value approximately double that of the 15 mm hole. The maximum corresponds in percent changes from the original of about 80% for the 15mm hole and 160% for the 45mm hole. The distance from the hole over which the potential is significantly changed is roughly the same as the hole diameter on each side. Changes at a greater distance than this are less than 10% of the original value. There are some small changes extending over all of the remaining area of the plate.

Changing the current input probes to a location midway along the vertical sides of the laminate, so that the current is flowing broadly perpendicular to the fibre direction changes the general

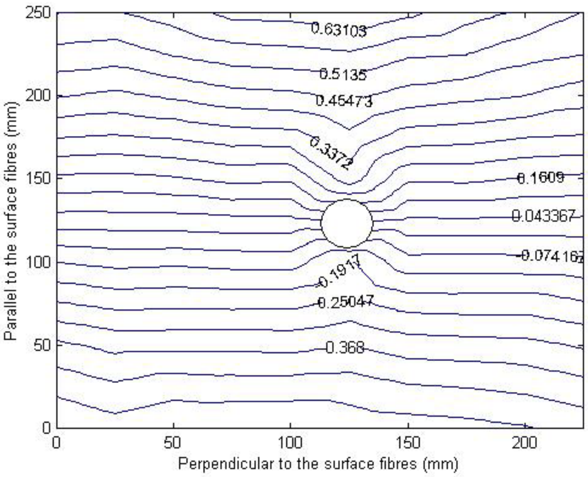


Figure 5: Quasi-isotropic plate with 15mm hole showing distorted potential field around hole. Current input bottom surface mid point horizontal perimeter.

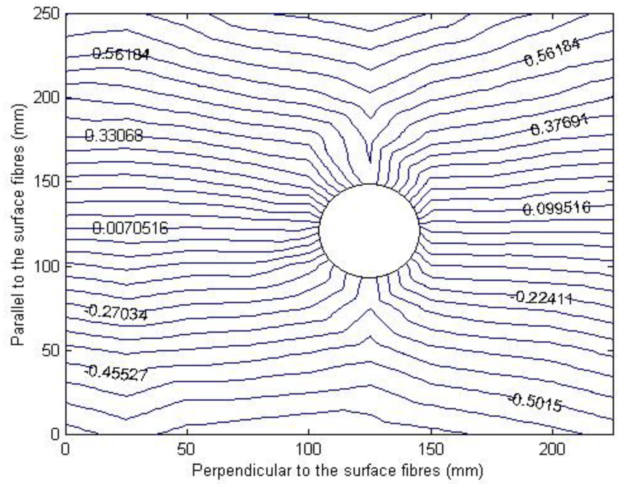


Figure 6: Quasi-isotropic laminate with 45mm diameter hole. Current input as for figure 5.

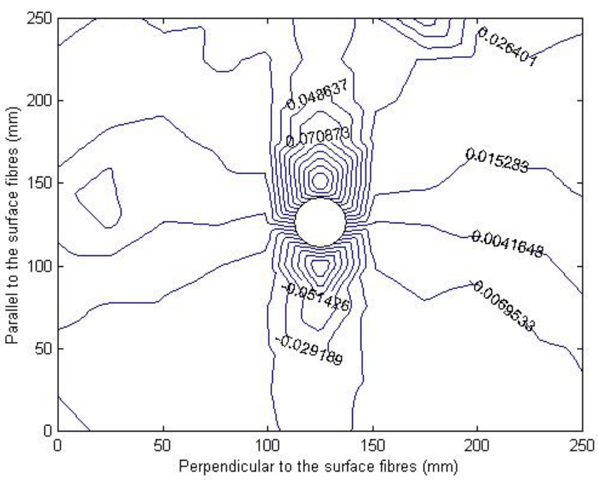


Figure 7: Contours of equi-potential change of quasi isotropic laminate with 15mm hole.

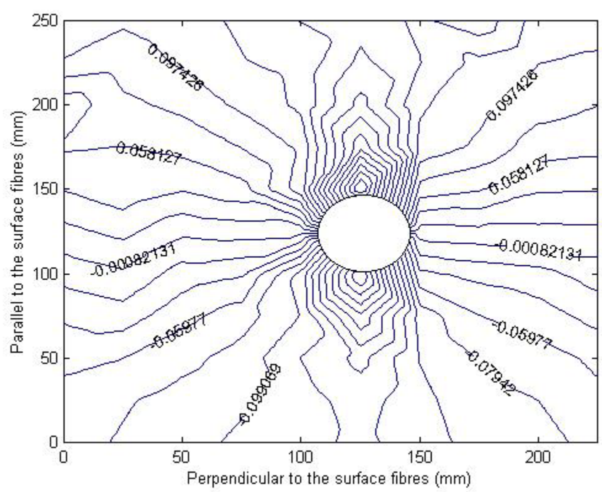


Figure 8: Contours of equi-potential change for 45mm hole. Conditions as for figure 7.

orientation of the equi potential contours, although the absolute values of the potential are greater. In this direction of current flow, equi potential lines are parallel with carbon fibres on the upper surface. It was found with this location of current input probes, that there was little change in the potential field in the vicinity of the hole, and damage in the form of a hole, with this orientation of the current flow could not be detected.

Potential changes arising from impact damage

Figure 9 shows the potential field measured after impact of 8 Joules on a cross ply laminate. The local field distortion around the impact damage can be seen. This field was produced with current introduced on the bottom surface of the laminate. Figure 10 shows a two dimensional plot of the % changes in potential resulting from the impact plotted as a function of distance from the impact centre along the fibre direction. It will be seen that similar behaviour to that found with the holes is observed. A peak in the percent change is found a short distance from the centre of impact, extending in the direction of the fibres, followed by a decline to changes of a few percent, achieved at a distance of 120 mm from the centre of impact. The maxima in % change are less than achieved with the holes, being 40% change for a 6 J impact and a 60% change for an eight joule impact for 43 mm and 89 mm diameter delaminations.

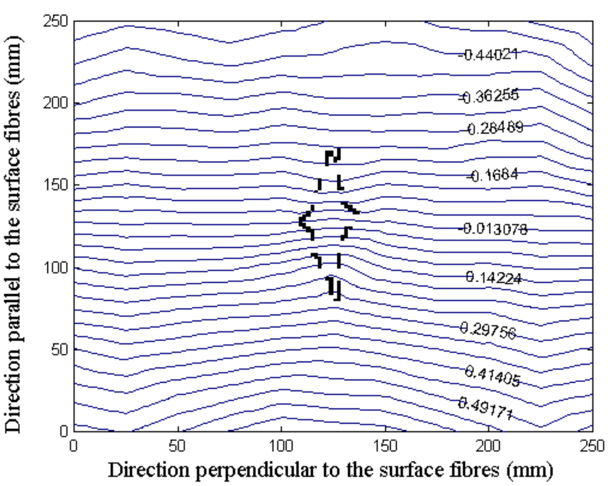


Figure 9: Potential field arising from impact of 8 Joules on cross ply laminate.

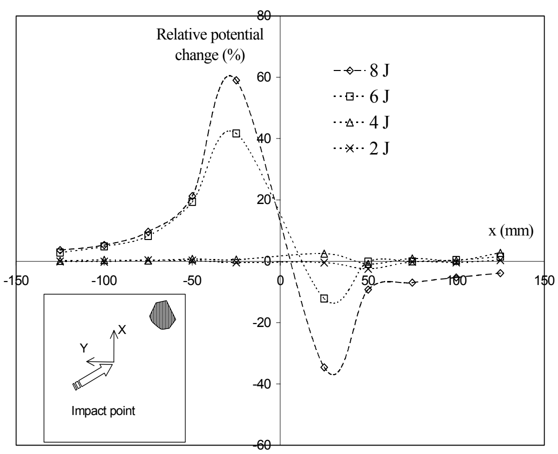


Figure 10 Section through distribution in figure 9 showing % change in potential as a function of distance in the fibre direction from the centre of the delamination.

FINITE ELEMENT ANALYSIS- SINGLE DELAMINATED LAYER

Finite element analyses were performed on quasi-isotropic material with the current introduced at the mid point of the horizontal perimeter edges, on the top and bottom surfaces. It was found that for all locations of current introduction and sizes of delamination, no damage could be detected with current introduced on the bottom surface. This is in contrast to the behaviour found for real delaminations (e.g. figure (9)) which could be detected with current introduced on both the top and bottom surfaces.

In simulations, delaminations could only be detected with current input on the top (instrumented) surface. Figure 11 shows a typical potential change field for a single delamination on the 0/45 interface. Relative to the potential values before delamination, the maximum percent change is high, its value depending on the size and location of the delamination. Moving the delamination from the centre position shown in figure 10 tends to increase the potential changes relative to the original values. Changes up to 50% of the original value were found for certain positions.

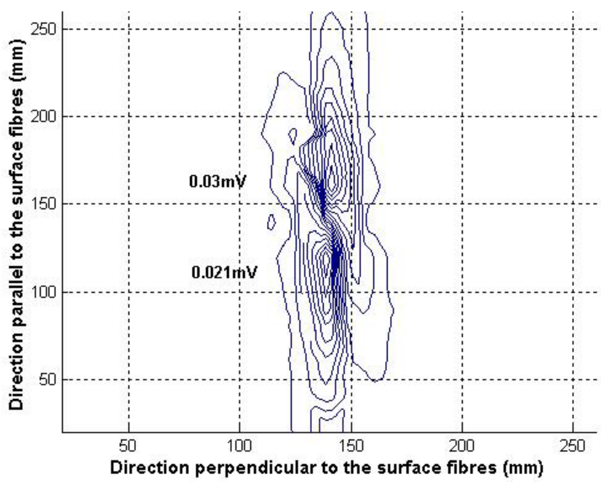


Figure 11: Finite element simulation of contours of equi-potential change in quasi-isotropic laminate with single delamination of size 32x51mm^2. Current input on top surface, mid points of horizontal perimeter edge

DISCUSSION

The observation that potential fields in multi-directional laminates are largely independent of lay-up type is of considerable importance. It implies that lay-up is not going to be an important factor in determining potential fields in a composite structure. Current flow in the directions of high resistance in individual laminae is small, but these directions coincide with directions of low resistance in adjacent contacting laminae, along which significant current can flow. Together the mutually misoriented laminae appear to produce an equi-potential field on the external surfaces, despite the gross anisotropy within individual laminae.

Current input location does significantly influence potential contours; this influence extends to the equi-potential change fields produced by holes, impact and delamination damage. The extent of the change fields and their magnitude appear to be both dependent on the current input location, and whether the inputs are on the same side as the measured field or on the opposite surface. In some configurations damage was detectable with one current location and almost undetectable with another. This suggests that current switching to provide alternative current locations will be important in practical damage detection systems based on this principle.

The finite element model has demonstrated good accuracy in simulating potential fields in undamaged laminates. The field orientation and distribution is accurately matched to experiment in the centre of the laminate with some errors at the edges. However the absolute values of potential are significantly in error if experimental values of inter laminae conductivity are used. The discrepancy could be associated with the way in which the FE software models interface contacts. The model has proved a valuable tool in simulating potential distributions for many different locations of damage and current input locations.

The response of potential changes to delamination and impact damage is encouraging. As figure 10 shows, changes of up to 60% were found adjacent to the damage. More importantly, changes of up to 3% were found at distances in excess of 100 mm from the damage centre of impact damage with a half width of 18 mm. This suggests that a network of probes of spacing 200 mm could detect whether damage had occurred. Whether it would be sufficient to locate as well as detect damage is the subject of further work.

CONCLUSIONS

(1) Investigations of the potential distribution on current carrying cross-ply and quasi-isotropic laminates, 280x280x2 mm, has shown little difference in the potential field on the surface in the two types of laminate.

(2) Experiments to measure potential distributions on cross ply composites after impact damage, show substantial changes in potential. Detectable changes in potential were found at distances in excess of 100 mm from the damage centre.

(3) Calculated potential distributions on laminates agreed well with those determined experimentally. The predicted size of the changes was smaller than those measured experimentally. It is believed that fibre fractures, present experimentally, but not present in the simulation were responsible for the differences.

(4) Damage could not be detected with current input probes in certain configurations with respect to the fibre orientation. This suggests that practical systems for damage detection using this technique will have to switch current inputs over a range of locations to be sure of detecting damage.

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